Techniques for Holistic Quantification of Performance, Portability, and Productivity

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Ψ, Quantitative Performance Portability

The **harmonic mean** of performance efficiency on a set of platforms

$$\Psi(a,p,H) = \begin{cases} \dfrac{|H|}{\sum_{i \in H} \dfrac{1}{e_i(a,p)}} & \text{if } i \text{ is supported } \forall i \in H \\ 0 & \text{otherwise} \end{cases}$$

$e_i(a,p)$ = efficiency of application a for input problem p.
H = set of platforms of interest

- Has desirable properties:
  - Supports many definitions of application/problem/efficiency/platform
  - Improving any result improves the metric
  - Non-portable code (i.e. performance of 0 on a platform) has score of 0
  - Easy to compute

S.J. Pennycook, J.D Sewall, V.W. Lee, "Implications of a Metric for Performance Portability" in *Future Generation Computer Systems*, 2017

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Code Divergence: quantitative portability/productivity

- Previous metric is completely orthogonal to productivity
  - 'Duct-tape' apps with totally distinct code for each platform compared to single-source applications
- We introduced code divergence:
  - Average of code distance between each pair of platforms
  - Use Jaccard distance of lines of code: $\frac{|c_i \cup c_j| - |c_i \cap c_j|}{|c_i \cup c_j|}$
- Has desirable properties:
  - 'Duct-tape' apps have divergence of 1
  - Single-source apps have divergence of 0
  - Partially specialized codes fit in between

[1] S.L Harrell, J. Kitson et al., "Effective Performance Portability", in *Proceedings of P3HPC*, 2018

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Code Divergence – Simple Example

Codebase 1

shared.cpp:

```
void whereami()
{
#ifdef CPU
  printf(“CPU\n”); ← 1 line specific to CPU
#else
  printf(“GPU\n”); ← 1 line specific to GPU
#endif
}
```

Divergence = (8 – 6) / 8 = 0.25

Codebase 2

cpu.cpp: ← entire file specific to CPU

```
void whereami()
{
  printf(“CPU\n”);
}
```

gpu.cpp: ← entire file specific to GPU

```
void whereami()
{
  printf(“GPU\n”);
}
```

Divergence = ((4 + 4) – 0) / 8 = 1.0

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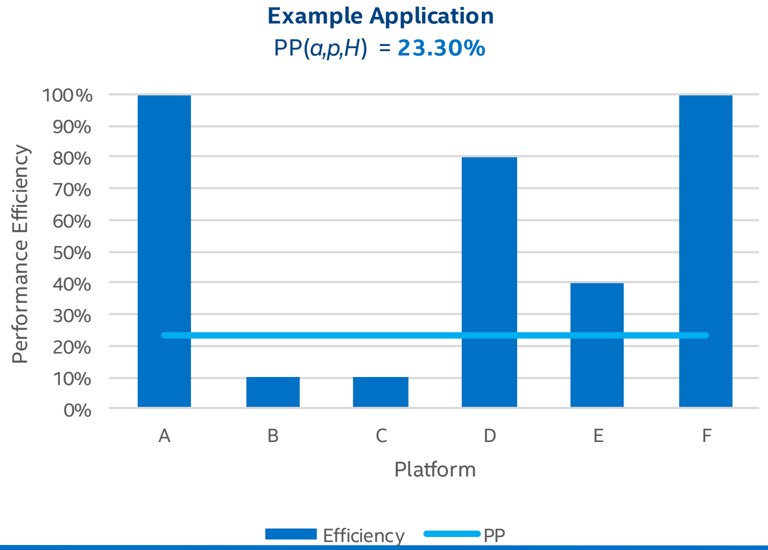
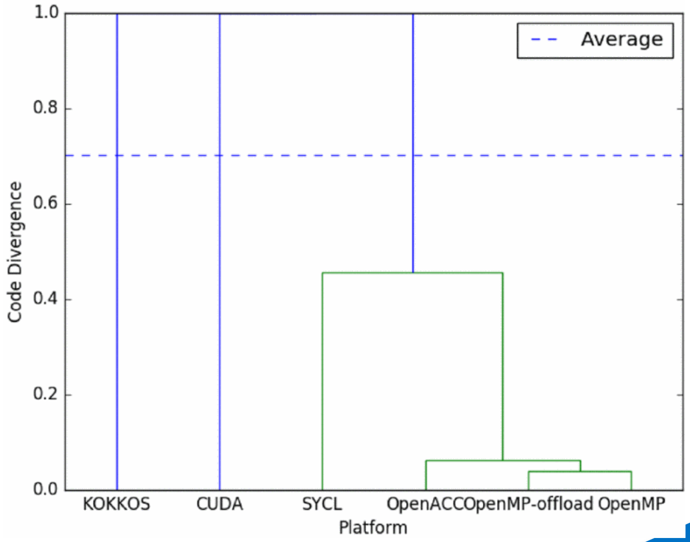
Combining metrics

- These metrics are complementary: one captures performance & portability, another productivity

Performance & Portability



Productivity



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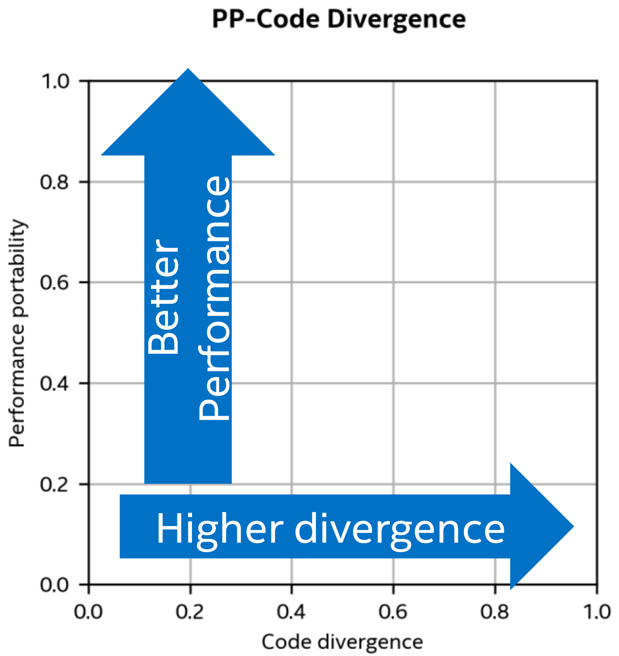
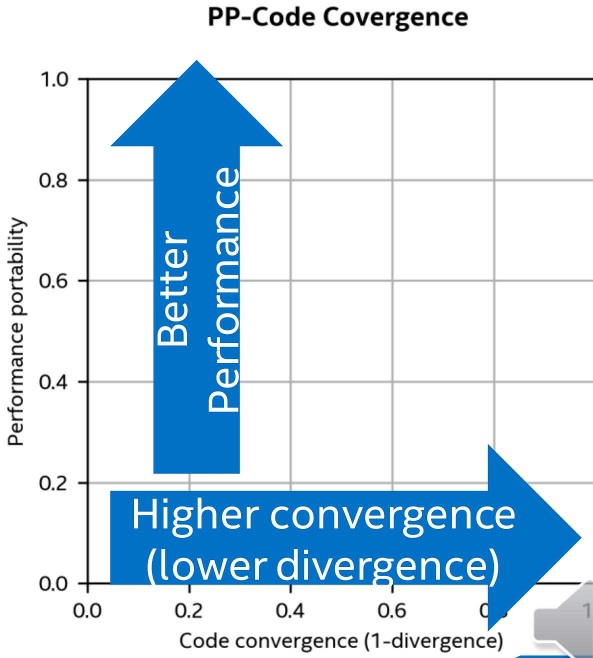
Combining metrics

- Plotting metrics in 2D can be illuminating. Select platform set, use for both PP and Code Divergence computation



- Code Divergence is the right metric, but it doesn't plot well
- Rather, use 'Code Convergence' (1- Code Divergence)



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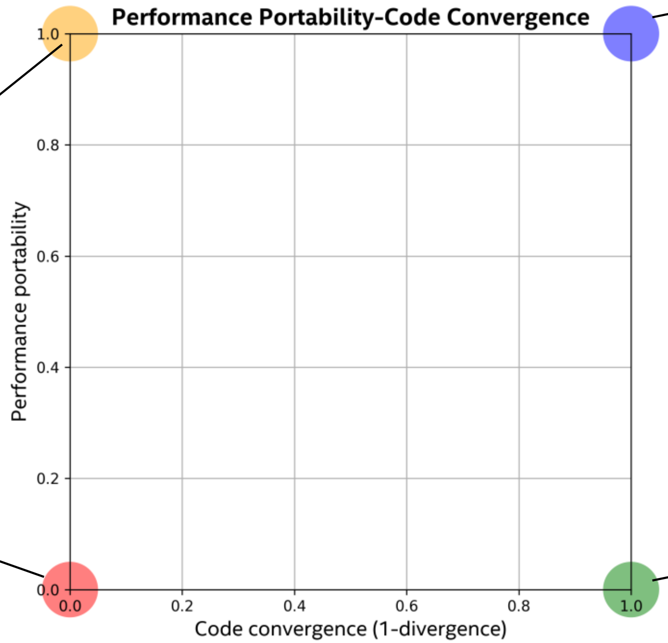
Boxing the combined graph



Perfect performance portability, total divergence

Perfect performance portability, total convergence

No performance portability, total divergence

No performance portability, total convergence

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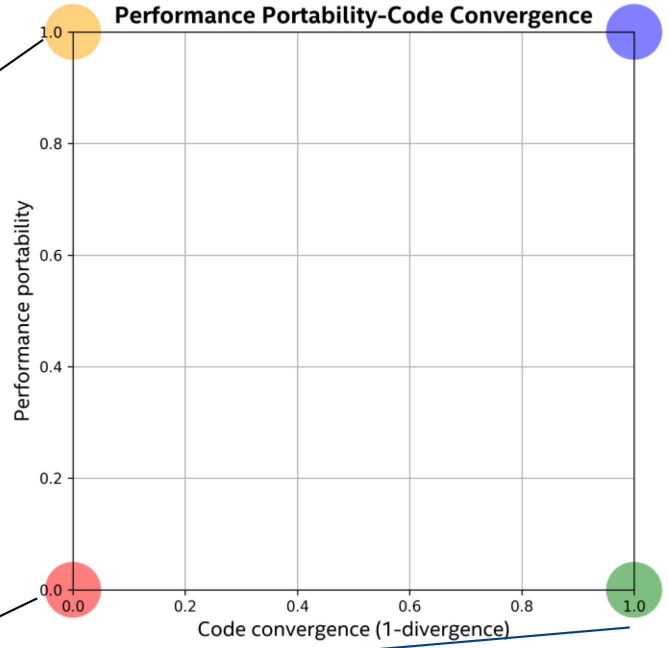
Boxing the combined graph

Can always construct this by combining (disparate) implementations that are best for each platform of interest.
AKA "the duct tape solution"



PP=0 axis is of little interest---code doesn't run on one or more platforms!

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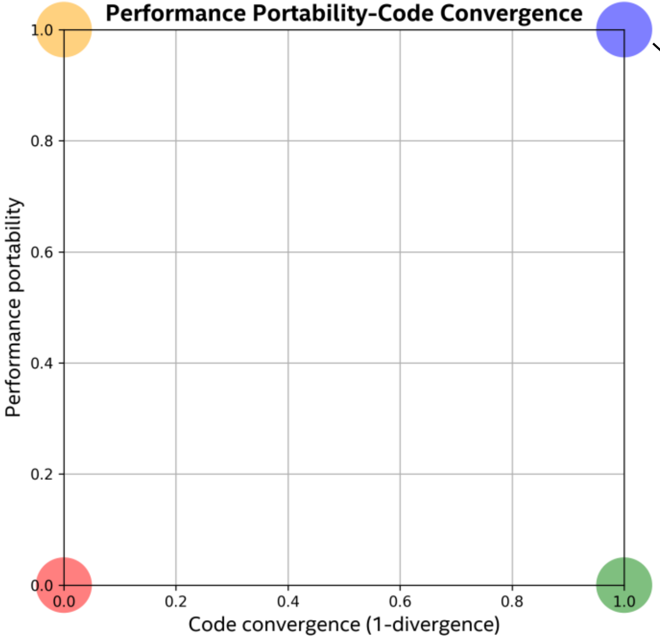
Boxing the combined graph



The Promised Land: single-source, best performance on all platforms (not realistic!)

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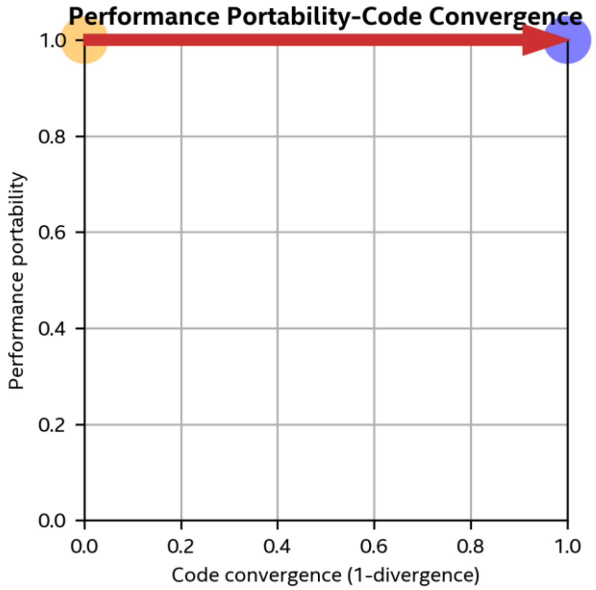
Translation in the PP-CC Plane

- Given 'duct-tape' application, how do we get the best case?
- PP and CC are linked
- CC = 1/PP = 1 are very hard to achieve, but settling for close to these limits has opportunities
  - Heroic (magic?) compilers needed for strict increases



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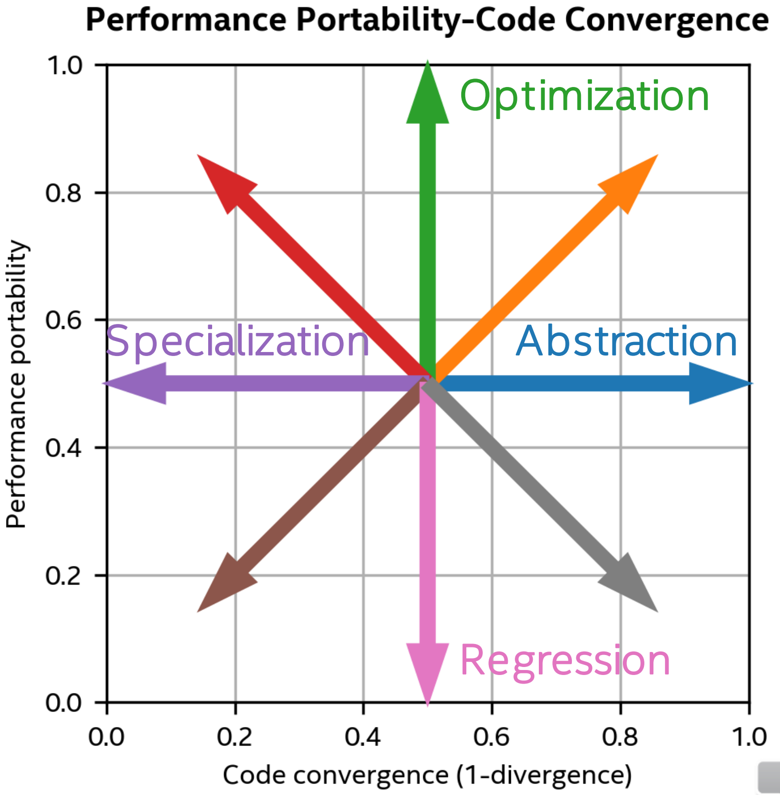
Translation in the PP-CC Plane

- Movement can be broadly described in terms of the axes (assume fixed platform set)
  - More abstraction -> Higher convergence
  - Less abstraction == specialization -> lower convergence
  - Better optimized code -> Higher PP
  - Regressed code -> Lower PP
    – Never a standalone goal, but a side-effect



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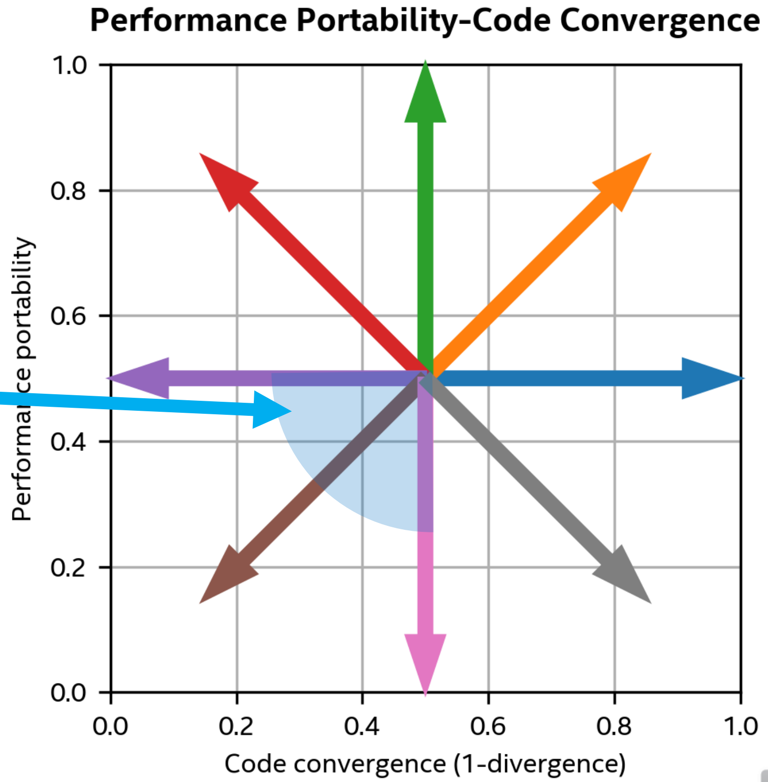
Translation in the PP-CC Plane

Specialization/Regression quadrant:
Includes Specialization/Regression axes
Almost never an actual goal.
Hypothetical causes:

- Feature added that decreases performance (possibly specialized)



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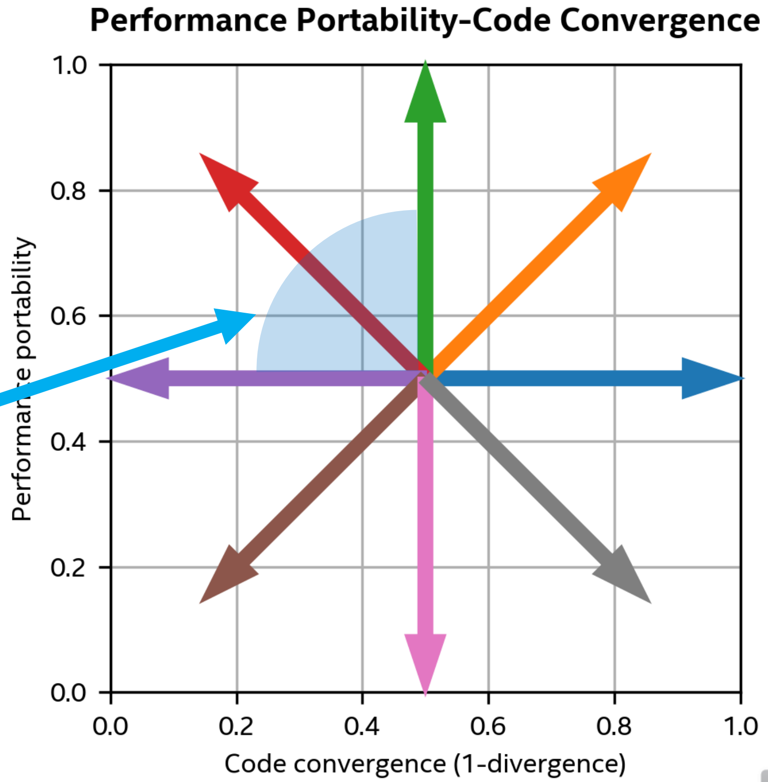
Translation in the PP-CC Plane

Specialization/Optimization quadrant:
Very typical scenario:
1. Relatively convergent codebase
2. Identify lagging platforms
3. Introduce specializations to improve performance

Considerations:
- How fine-grained is specialization mechanism?
- What is the trade-off of CC vs. PP?



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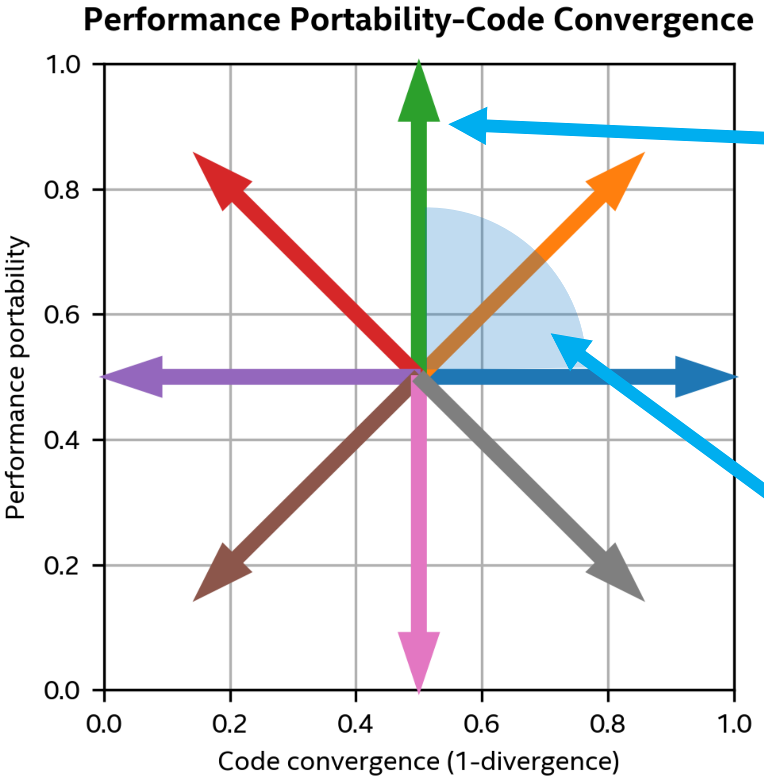
Translation in the PP-CC Plane



Optimization axis:

A change to common codebase increases overall PP

- Due to performance gains on a single platform or across multiples

Optimization/Abstraction quadrant:

Code is more convergent and more performant!

- Tool/backend improvements
- Magic compilers

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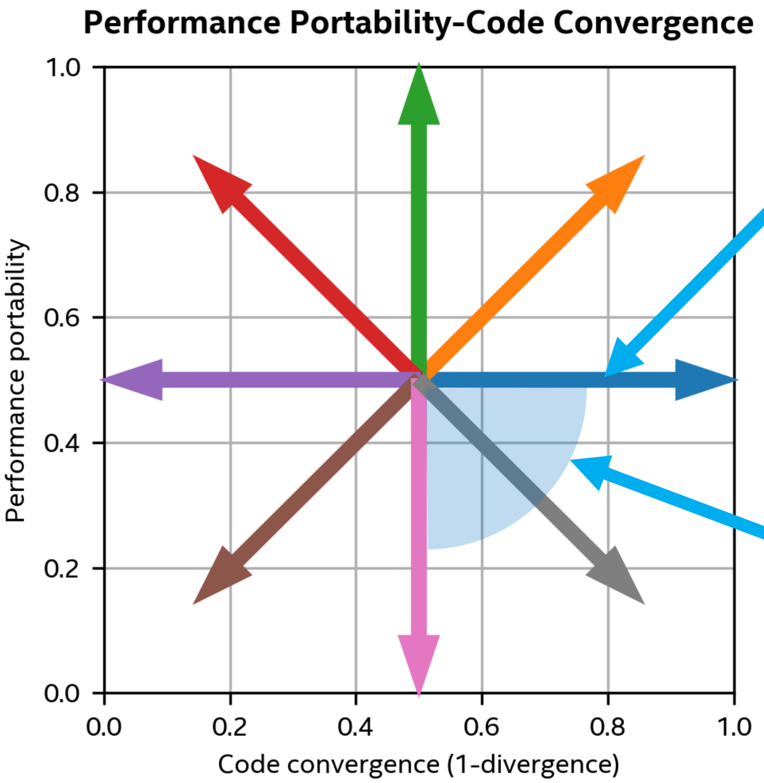
Translation in the PP-CC Plane



Abstraction axis:

Refactoring code increases CC, doesn't affect performance.

Regression/Abstraction quadrant:

Abstraction penalties arise.
As abstractions are introduced, performance on some platforms may decrease

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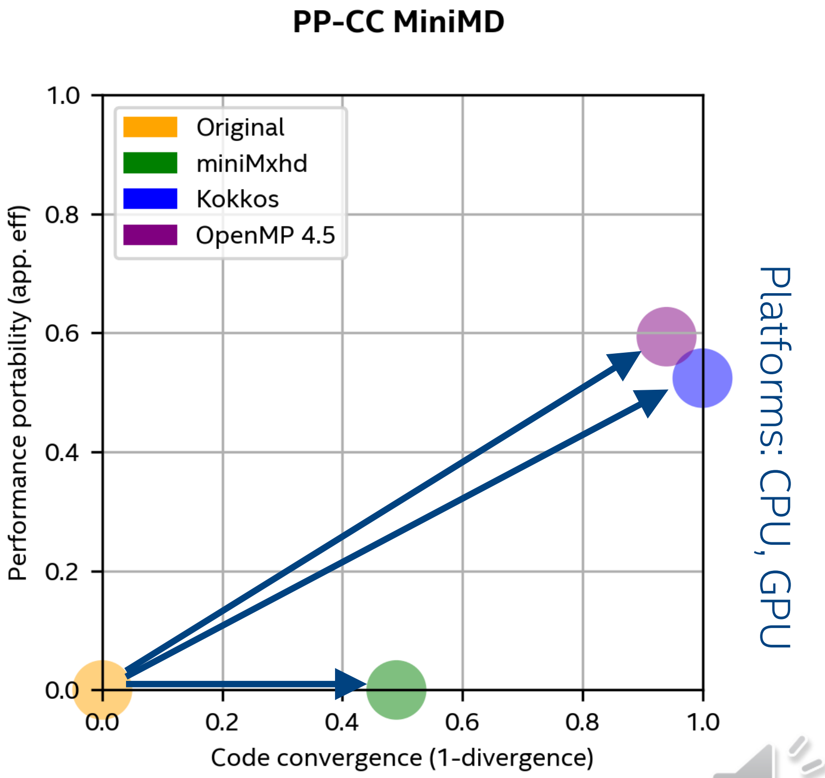
MiniMD

- Venerable Mantevo proxy for LAMMPS
- Original OpenMP code is CPU-only
- miniMxhd developed by Intel
  - Highest performing CPU version
- Kokkos version developed by Sandia
  - Highest-performing GPU version
- OpenMP 4.5 version developed by Intel
  - Achieves highest PP due to highest CPU performance among GPU-supporting codes



Pennycook, Sewall, Hammond “Evaluating the Impact of Proposed OpenMP 5.0 Features on Performance, Portability, and Productivity”. SC P3HPC 2018

https://github.com/Mantevo/miniMD

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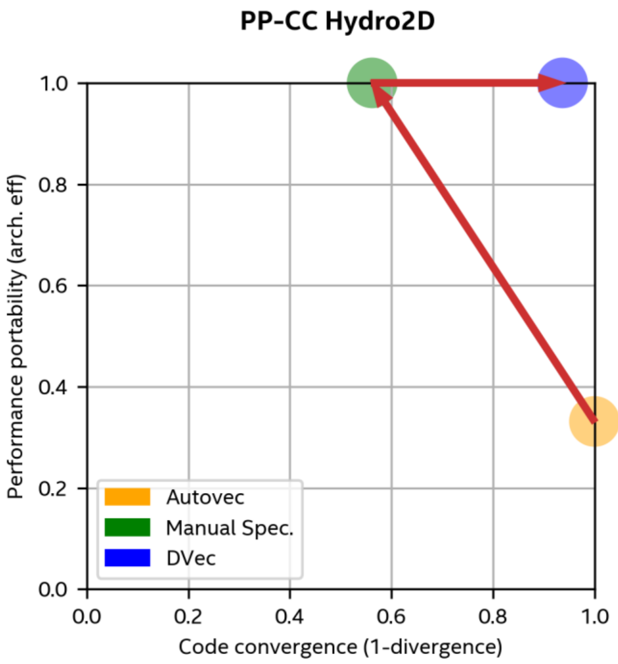
Hydro2D

- CEA benchmark code
- OpenMP code optimized by Intel
- Autovectorization performance poor, but single codebase
- Manual vectorization using intrinsics introduced for each SIMD ISA
  - High performance, less convergence
- Refactoring to a common vector abstraction results in matching performance, higher convergence.



Platforms:
CPU0,CPU1,CPU2,CPU3

Sewall, Colin de Verdiere, "From 'Correct' to 'Correct and Efficient': A Case Study with Hydro2D". Intel Xeon Phi Programming Gems, Reinders et al. eds 2015.

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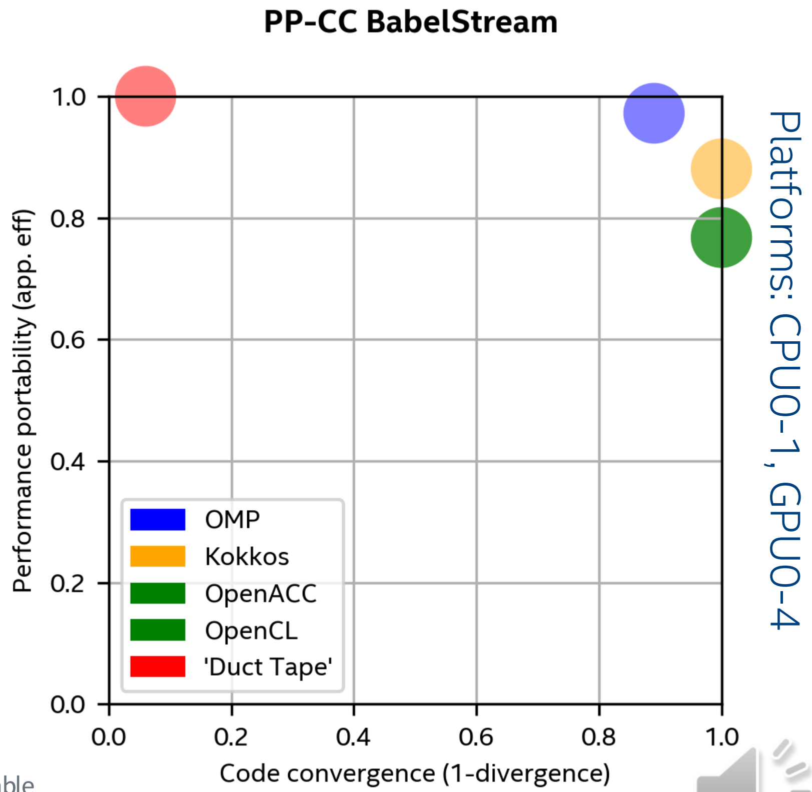
Babelstream

- Multi-platform STREAM code
- Many implementations
  - Minimal effort made to reduce divergence
- Synthetic 'Duct Tape' app constructed from all codes
  - Highest PP, low CC
- OpenMP has slightly different codes for CPU and GPU (omp target)
  - High PP, some reduced CC
- Kokkos, OpenACC, and OpenCL CC > 0.999
  - OpenACC and OpenCL have nearly identical PP



Deakin T, Price J, Martineau M, McIntosh-Smith S. GPU-STREAM v2.0: Benchmarking the achievable memory bandwidth of many-core processors across diverse parallel programming models. 2016. Paper presented at P^3MA Workshop at ISC High Performance, Frankfurt, Germany.

https://github.com/UoB-HPC/BabelStream

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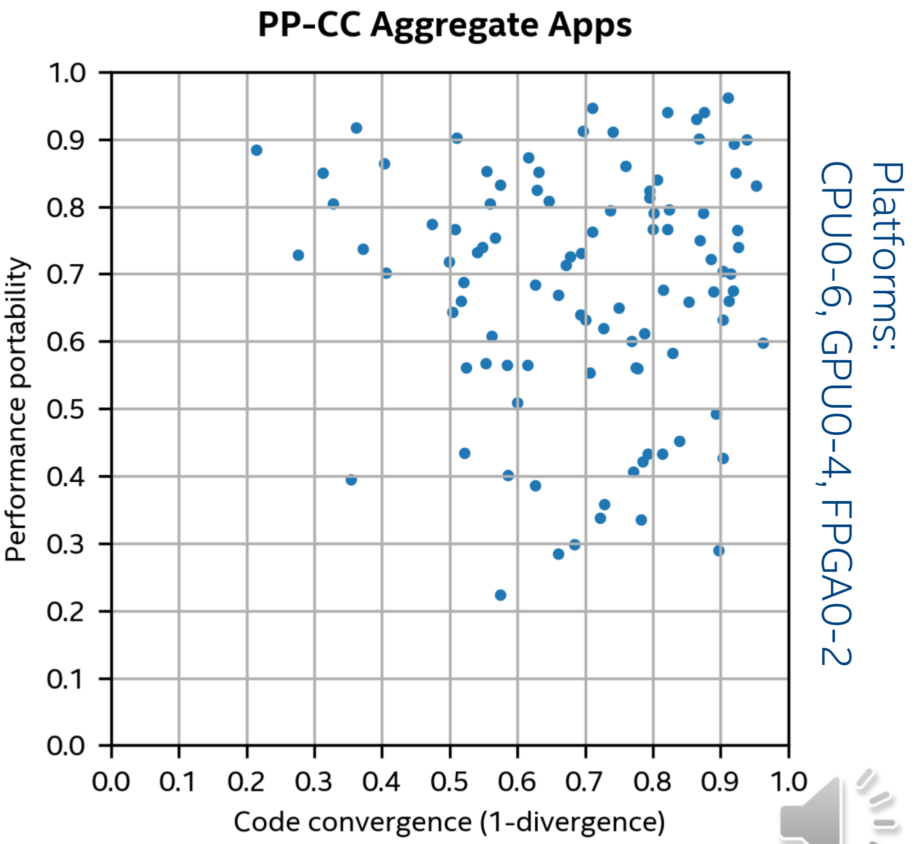
Aggregate analysis

- How can we apply this to a group of codes running on the same platforms?
  - What does it tell us?
  - How can we use it to measure success
    - Of codes
    - Of tools
- Synthetic data presented for exposition



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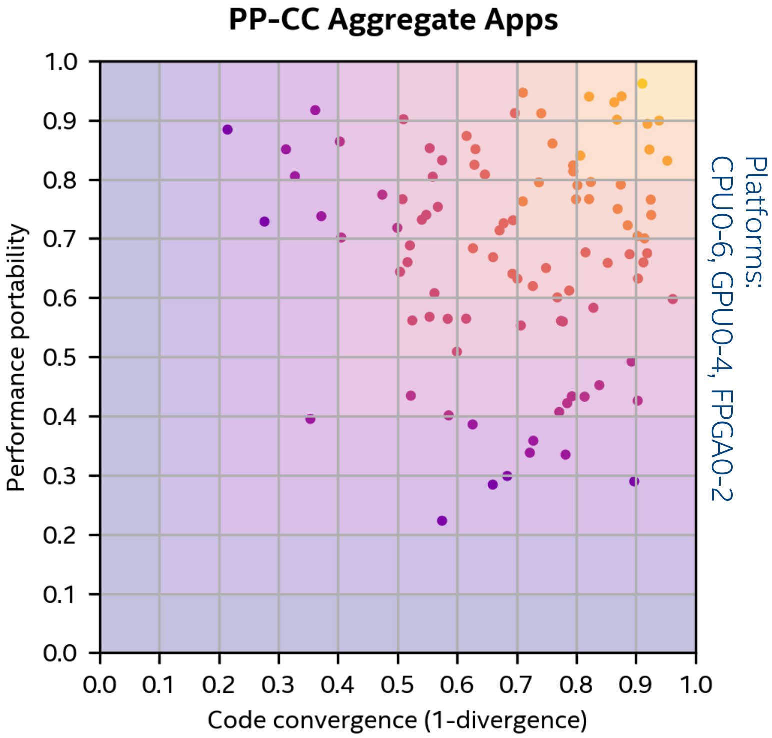
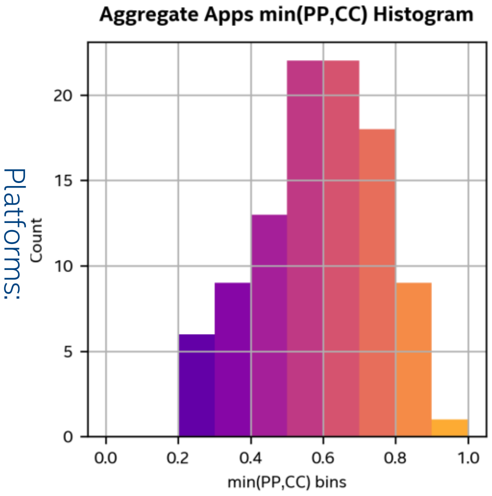
Aggregate analysis

- Given goal of having codes in the upper-right part of chart:
  - Score each point with min(PP,CC)
  - Sort into bins of length 1/10
- Extract statistics
  - Minimum is 0.21
  - Median is 0.60
  - Maximum is 0.91





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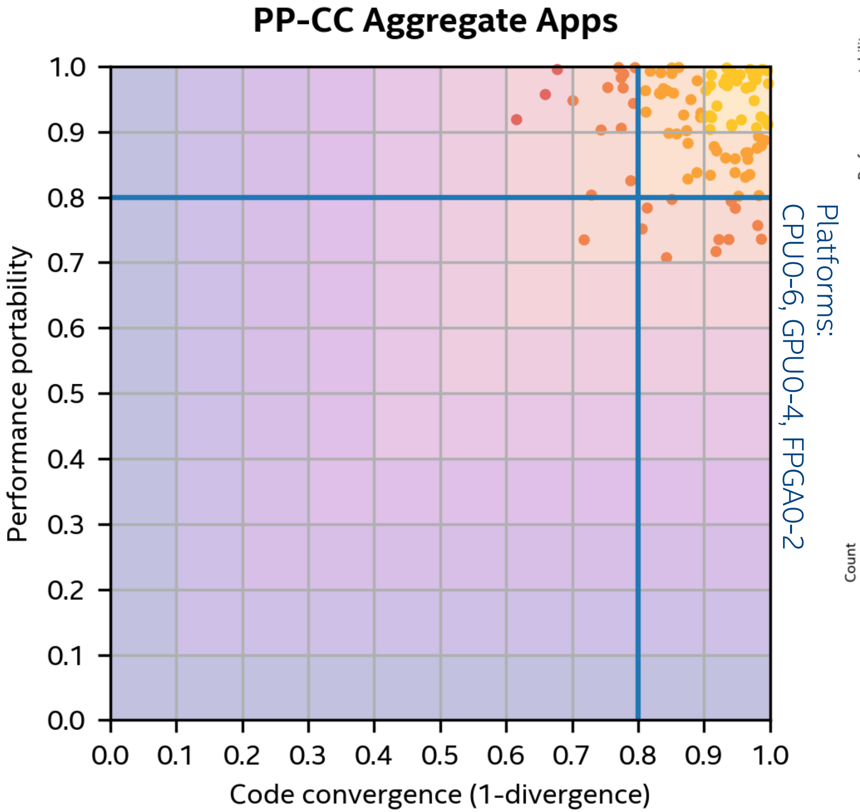
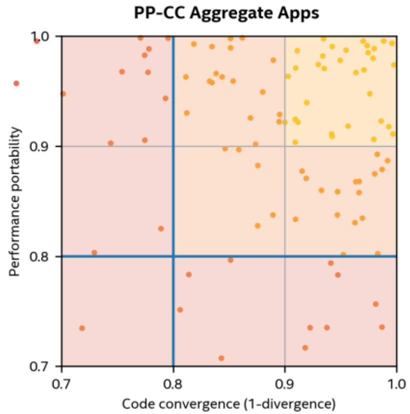
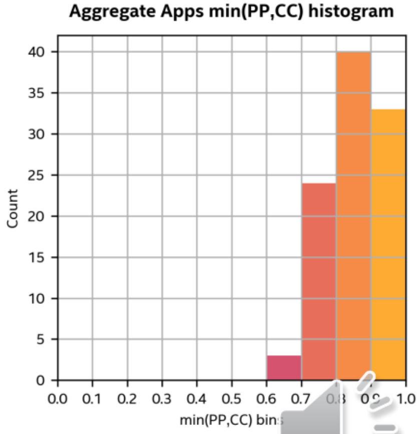
Aggregate analysis

- Optimized codes/tools
- Set goal that 50% of codes must score 0.8 or higher
- Stats:
  - Minimum is 0.62
  - Median is 0.86
  - Maximum is 0.993







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Review

- Performance portability and code divergence scores are complementary in a P3 context
- Combining them in a 2D plot—with attention to platforms and adjustment to code convergence—can reveal useful trends and patterns, both with single applications and aggregates
  - Seeing current status and setting goals in the PP-CC plane can give clues on how to proceed to improve application
- Methods derived from this are used as internal scoring metrics inside Intel to guide us to a more P3 future

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Future work

- The usefulness of P3 is inherently subjective
  - Need more data on what people are satisfied with, and how it looks in these visualization
- Varying platforms in these graphs is a promising direction for understanding sensitivity in toolchains and hardware
- "Language shootout" applications for understanding relative strengths/weaknesses among programming tools
- More real data sets analyzed and published!

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Slide 17 – Measured by Intel & CEA: J. Sewall, G. Colin de Verdiere, "From 'Correct' to 'Correct and Efficient': A Case Study with Hydro2D". Intel Xeon Phi Programming Gems, Reinders et al. eds 2015.
Slide 18 – Measured by University of Bristol: T. Deakin, J. Price, M. Martineau, S. McIntosh-Smith. GPU-STREAM v2.0: Benchmarking the achievable memory bandwidth of many-core processors across diverse parallel programming models. 2016. Paper presented at P^3MA Workshop at ISC High Performance, Frankfurt, Germany.

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